Spectrum flattening of white OLED with photonic crystal patterned capping layer

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Abstract - A photonic crystal patterned capping layer is proposed to enhance the extraction and flatten the spectrum of white organic light-emitting diode. Spectrum with efficiency variation of only 0.48dB in the entire visible range is obtained.

Introduction

Since the invention of white organic light-emitting diodes (WOLED) by Kido et al. in 1993, WOLEDs have drawn increasing attention as a solid state light source and backlight in liquid crystal displays and even in full-color OLEDs display because of the low operating voltage, wide view angle and high contrast [1-4].

Photonic crystal (PC) structures have been proven effective in enhancing the light extraction efficiency of light emitting diodes [5-7]. But to date, there are still not any discussions about the effect of PC on the shape of the spectrum. In this paper, we proposed to use a photonic crystal (PC) capping in an inverted top emitting OLED (ITE-WOLEDs) structure to simultaneously enhance the light extraction efficiency and to flatten the broadband spectrum. ITE-WOLED structures have significantly better performance in the integration with TFT circuits [1,2,4] but usually they would not considered in the fabrication of white OLEDs due to the strong cavity effect which narrow the spectrum. The PC patterned capping layer enhance the light extraction efficiency and flatten the spectrum by introducing the leaky modes which weaken the cavity effect. Numerical simulations using three dimensional (3D) finite-difference time-domain (FDTD) method show that the PC patterned capping layer can enhance the extraction efficiency up to 46.5% with a flat spectrum. The maximum variation of the extraction efficiency in the entire visible range can be reduced to 0.48 dB.

Design and computational model

Figure 1(a) shows the computational model of the proposed design of an ITE-WOLED with a PC-patterned capping layer. To simplify the calculation, all organic layers including the electron transport layer, emission layer, hole injection layer and hole transport layer are assumed to have the same refractive index n_0 = 1.7 and absorptions are neglected. The anode layer is assumed to be transparent with a refractive index of n_a = 1.8. The high reflectance cathode layer is modeled with perfect electric conductor (PEC).

As shown in Fig. 1(b) and (c), we will study both PCs with square lattice and triangular lattice. The lattice constant is set to a. The emission layer is placed at the center of the organic layers which have a total thickness of 0.5a. The anode layer thickness is assumed to be 0.05a and the capping layer thickness is 0.45a. The computational size x×y is 7a×7a. The PCs in Figs. 1(b) and (c) is a 6×6 square lattice and a 6×7 triangular lattice respectively.

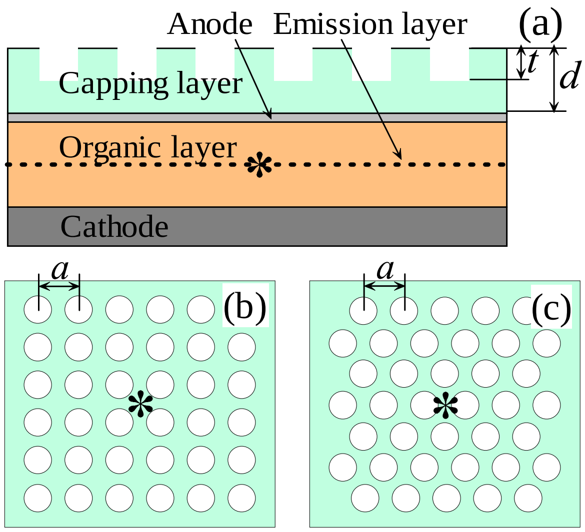

Fig. 1. Design model. (a) The side view of an ITE-WOLED with a PC patterned capping layer. (b) The top view of an ITE-WOLED with a square lattice PC patterned capping layer. (c) The top view of an ITE-WOLED with a triangular lattice PC patterned capping layer.

A three dimensional finite-difference time-domain method with uniaxial anisotropic perfectly matched layer (UPML) boundary condition is used to calculate the extraction efficiency [8]. All the layers of the ITE-WOLED are terminated by UPML. The extraction efficiency is defined as the fraction of emitted flux through the top and bottom surfaces of the ITE-WOLED to the total emitted flux [5]. To avoid the influence of evanescent wave and to separate the radiation modes from the waveguide modes, the top detecting surface is put at distance a from the ITE-WOLED top emitting surface [9]. An electrical point dipole excited by a Gaussian pulse is inserted at the center of the organic layer as the source. The extraction efficiency as a function of frequency is obtained by discrete Fourier transform in a single simulation run.

To simulate the extraction efficiency with arbitrary polarized dipoles corresponding to spontaneous emission, we use the average efficiency of dipoles polarized in x-y

and z [9],

$$\eta = \frac{2}{3}\eta_{xy} + \frac{1}{3}\eta_z \qquad (1)$$

In the simulations, we determine both the maximum extraction efficiency η_{max} and the maximum variation of the extraction efficiency, $R = -10\log(\eta_{max}/\eta_{min})$, where η_{min} is the minimum extraction efficiency, in the visible range 400-700 nm. The parameter R is used to measure the flatness of the extraction spectrum.

Simulation results

We have compared the extraction efficiencies of ITE-WOLED without capping layer, with uniform capping layer, and with PC patterned capping layer. To flatten the spectrum and enhance the efficency, we have optimize the performance of the ITE-WOLED with PC patterned capping layer by studying the effects of variations in the refractive index n_c, thickness d, and PC hole depth t of the capping layer.

Figure 2 compares the extraction efficiencies of different ITE-WOLED configurations. Crosses represent the extraction efficiency for an ITE-WOLED without capping layer. We observed that the extraction efficiencies in the entire visible range of 400-700 nm are lower than 25.4% and the minimum extraction efficiency is only 18% which means a relatively large variation in the extraction efficiency of R = 1.5 dB. The solid circles represent the extraction efficiency for an ITE-WOLED with a uniform capping layer. The thickness of the capping layer is 0.45a and the refractive index is 2.5. The uniform capping layer leads to higher reflection at the interfaces. The maximum extraction efficiency is ~45% near 500 nm and the minimum extraction efficiency is ~10% near 400 nm. The maximum variation R is therefore 6.5 dB.

We then use PC with square lattice and triangular lattice to enhance the extraction efficiency and flatten the spectrum in visible range. The solid triangles represent the extraction efficiency for a PC capping layer with triangular lattice with optimized parameters. The capping layer has a thickness of 0.45*a* and the refractive index is 1.8. We observed that the spectrum is significantly flattened in the entire visible range. The maximum efficiency is 30.7% and R = 0.48 dB. The solid squares represent the extraction efficiency of a PC with an optimized square lattice. The refractive index is 2.5 and the thickness is 0.25*a*. The maximum extraction efficiency is 46.5% and R = 0.89 dB. We note that the extraction efficiencies are almost twice that of the conventional ITE-WOLED in the entire visible range. The maximum variation in the extraction efficiency is also reduced from 1.5 to 0.89 dB.

Summary

In summary, we have numerically studied the enhancement of the extraction efficiency and flattening the spectrum of ITE-WOLED with PC patterned capping layer using 3D-FDTD method. We found that a square lattice PC patterned capping layer with refractive index 2.6 and thickness 0.25*a* where *a* is the lattice constant can enhance the efficiency to 46.5% with a variation in the extraction efficiency of only 0.89 dB in the entire visible range. An ultra flat extraction spectrum with a variation in the extraction efficiency of only 0.48 dB in the entire visible range can be obtained using a PC patterned capping layer with triangular lattice, refractive index 1.8 and capping layer thickness 0.45*a*. The maximum extraction efficiency is 30.7%. The results show that it is possible to fabricate white organic OLEDs with the inverted top emitting structure.

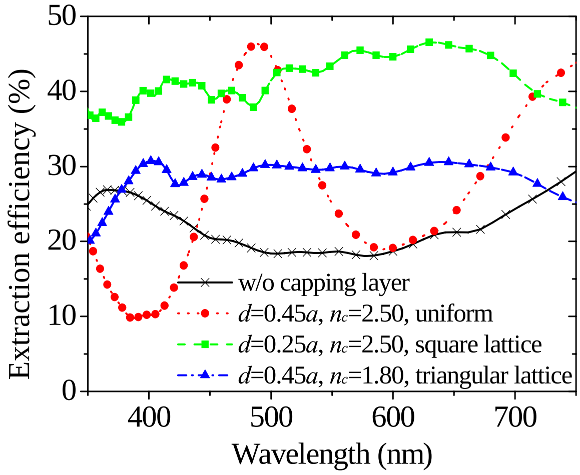

Fig. 2. Extraction efficiencies versus wavelength. Crosses and circles represent the extraction efficiency without capping layer and with a uniform capping layer of refractive index 1.8 respectively. Squares represent a PC patterned capping layer with a square lattice. The refractive index is 2.5 and the thickness is 0.25*a*. Triangles represent a PC patterned capping layer with triangular lattice. The refractive index is 1.8 and the thickness is 0.45*a*.

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